

# $t\bar{t}$ pair hadroproduction in association with a heavy boson at the NLO QCD accuracy + Parton Shower

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**Abstract.** The PowHel framework allows to make predictions of total and differential cross-sections of multiparticle hadroproduction processes at both NLO QCD accuracy and NLO QCD matched to Parton Shower, on the basis of the interface between the POWHEG-BOX and HELAC-NLO codes. It has already been applied to study several processes involving a  $t\bar{t}$  pair in association with a third particle or hadronic jet. Our most recent predictions concern  $t\bar{t}V$  hadroproduction (with  $V = W$  or  $Z$ ), at both parton and hadron level, by considering different decay channels (hadronic and leptonic) of the heavy particles. In particular, we show the results of our phenomenological analyses under the same system of cuts also recently adopted by the CMS collaboration at LHC.

## 1. Introduction

In recent years significant effort was devoted to increase the accuracy of theoretical predictions for  $p$ - $p$  collision processes, in order to match the experimental capabilities of the LHC detectors. One line of development aims at providing refined automatic computations of fixed-order total and differential cross-sections with increased accuracy, leading to predictions of the final products of hard-scattering processes at the parton level. A second line of development, strongly tied to the first one, relies on the combination of these results with shower algorithms, able to track the evolution of these final-state particles to hadronization. In practice, to realize the combination between hard-scattering and parton shower, different matching schemes have been proposed, depending of the order of the perturbative expansion. At NLO accuracy two methods have dominated the literature in the last ten years, the MC@NLO [1] and POWHEG [2, 3]. Here we make use of the latter, as implemented in the computer program POWHEG-BOX [4].

The POWHEG-BOX provides an almost automatic and process-independent matching framework yet it requires some process-dependent input, that has to be specified by the user, process by process. Thus, it offers a framework to implement the matching of new processes, once one is able to provide all required input. In case of processes of some complexity already at the parton level, e.g. multiparticle production, this input can be conveniently computed by external codes.

Our PowHel package uses the HELAC-NLO [5] set of codes, to provide all matrix-elements required as input by POWHEG-BOX for the computation of cross-sections at the NLO + PS accuracy for  $t\bar{t}$  pair hadroproduction in association with a third particle. The output of PowHel are Les

Houches event (LHE) files [6], including events at the first radiation emission level. Additional radiation emissions can be simulated by further showering these events using Shower Monte Carlo (SMC) programs, such as `PYTHIA` [7] and `HERWIG` [8]. This can be done a-posteriori, since all essential process and event information needed at this purpose is already stored in the LHE files. Thus the full method can be exploited to produce predictions at the NLO level, at the first radiation emission level (LHE level), after parton shower (PS) and after PS + hadronization + hadron decay.

The total cross-sections as computed from LHE events are expected to have NLO accuracy, whereas the corresponding differential distributions have formally NLO accuracy up to higher order corrections, as LHE events also include the effect of Sudakov form factors embedded in the POWHEG formula. Therefore LHE predictions, as compared to NLO ones, are very useful to check the correctness of the implementation and to understand, as well, in which phase-space regions one could expect that the effects of higher-order corrections will sensibly modify the NLO distributions. On the other hand, predictions after the full SMC chain are the closest to the experimental results, allowing for an immediate comparison with the data collected in the detectors. Actually, in many experiments reconstruction procedures have been developed in order to reconstruct the intermediate unstable particles, like top quarks and heavy bosons, from which the final-state products are originated (bottom-up approach). We would like to emphasize however, that, once full high-accuracy simulations from the parton level down to the hadron level (top-down approach) are available, like in the case of `PowHel` + SMC, this reconstruction is unnecessary.

In this paper we concentrate on the case of  $t\bar{t}$ -pair hadroproduction in association with an heavy gauge boson,  $t\bar{t}W$  and  $t\bar{t}Z$ , that we have recently studied extensively in Ref. [9, 10], leaving the reader interested in our predictions for other  $t\bar{t}$ -X associated processes, like  $t\bar{t}j$ ,  $t\bar{t}H$  and  $t\bar{t}A$ , to previous works including `PowHel` predictions [11, 12, 13].

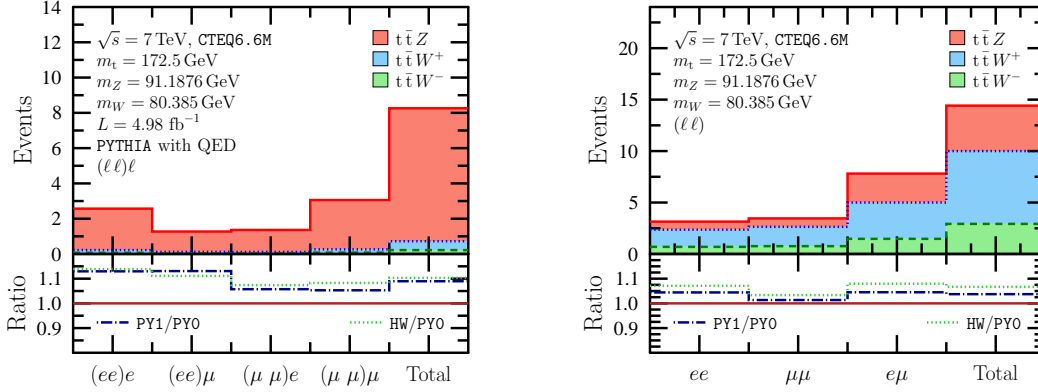
## 2. Results

$t\bar{t}Z$  and  $t\bar{t}W^\pm$  LO and NLO inclusive cross-sections as predicted by `PowHel` were already presented in Ref. [9, 10]. Here we emphasize that these predictions follow extensive checks and comparisons to the results of previous works presented by different authors in Ref. [14, 15], on the basis of different methods. Further predictions concerning several differential distributions at NLO and at NLO + PS accuracy were included, as for  $t\bar{t}Z$  hadroproduction, for the first time in Ref. [16] and [10], respectively, whereas, as for  $t\bar{t}W$ , in Ref. [9].

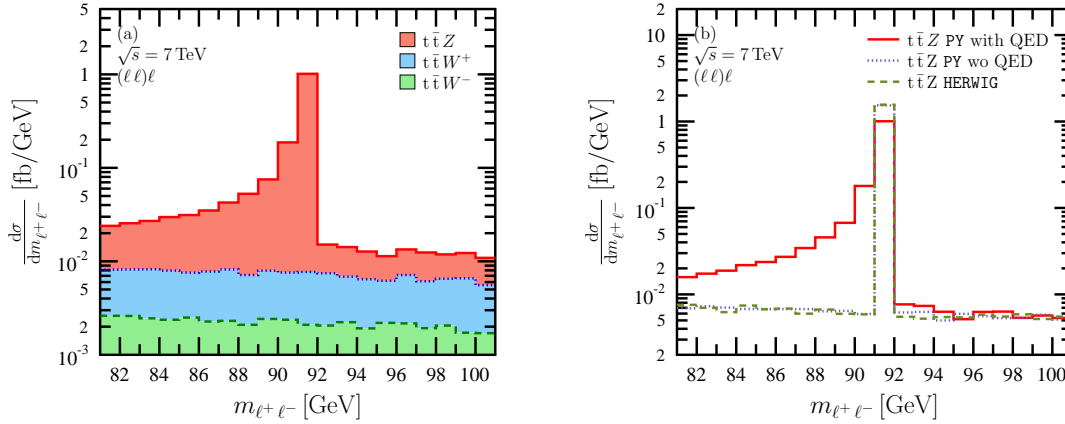
Our predictions use the following parameters:  $m_t = 172.5$  GeV,  $m_W = 80.385$  GeV,  $m_Z = 91.1876$  GeV,  $\sin^2 \theta_C = 0.049284$ ,  $\mu_R = \mu_F = m_t + m_V/2$ , where  $m_V$  is the mass of the vector boson, and the `CTEQ6.6M` PDF set available with the `LHAPDF` interface, with a 2-loop running  $\alpha_S$ . We adopted the SMC versions `PYTHIA-6.4.26` and `HERWIG-6.520`. We enforced stability of  $\pi^0$  in both, whereas  $\mu$  stability was enforced in `HERWIG`, to match the default in `PYTHIA`. All other hadrons and leptons were assumed to be stable or to decay with B.R. according to the default implementation of each SMC.

When making predictions at NLO + PS accuracy, we concentrated on two different channels, the trilepton and the same-sign dilepton ones, as also recently exploited by the CMS collaboration in Ref. [17]. Essentially, the trilepton channel selection aims at isolating the  $Z$ , decaying in  $\ell^+ \ell^-$  pairs, together with the  $t\bar{t}$  pair decaying semileptonically. The selection of the dilepton channel aims at isolating the  $W^\pm$ , decaying in  $\ell^\pm (\bar{\nu}_\ell)$ , again with the  $t\bar{t}$  pair decaying semileptonically. The list of cuts we adopted for this study is extensively detailed in Ref. [9].

In the trilepton channel, requesting the invariant mass of a pair of opposite-charge isolated leptons to be close to the  $Z$  mass, the contribution of  $t\bar{t}W^+$  and  $t\bar{t}W^-$  is suppressed with respect to the contribution of  $t\bar{t}Z$ , as shown in Fig. 1.a. The invariant mass of the reconstructed  $Z$  after cuts is shown in Fig. 2.a, by cumulating the results of the three processes. Pairs of opposite



**Figure 1.** Number of events in a) the trilepton and b) the dilepton channels at the  $\sqrt{s} = 7$  TeV LHC, as predicted by PowHel + PYTHIA, for an integrated luminosity  $L = 4.98 \text{ fb}^{-1}$ . The contribution in all possible channels are shown separately, as well as their sum in the last bin of each panel. The contributions due to  $t\bar{t}Z$ ,  $t\bar{t}W^+$  and  $t\bar{t}W^-$  are cumulated one over the other. To be compared with the experimental data in Fig. 4 and 6 of the CMS technical report [17], respectively. In the lower inset the ratios between cumulative results using different SMC (HW/PY) and between cumulative results obtained by neglecting and including photon radiation from leptons (PY1/PY0) are also shown.



**Figure 2.** Invariant mass of the Z reconstructed from same-flavour ( $\ell^+$ ,  $\ell^-$ ) pairs after the trilepton analysis, as obtained by PowHel + PYTHIA at the  $\sqrt{s} = 7$  TeV LHC: in panel a) the results corresponding to the different processes  $t\bar{t}Z$ ,  $t\bar{t}W^+$  and  $t\bar{t}W^-$  are cumulated one over the other, whereas in panel b) distributions obtained by using different SMC (PYTHIA, HERWIG and PYTHIA without photon radiation from leptons) are also shown, limited to  $t\bar{t}Z$ .

charge leptons, emitted by heavy particle decays, turned out to be quite insensitive to SMC effects, allowing for a good reconstruction of heavy objects. This opens good perspectives for the study, in the trilepton channel, of even other neutral boson candidates, like an exotic  $Z'$ . Even if further photon emissions from the emitted leptons smear the  $Z$  peak in the  $(\ell^+, \ell^-)$  invariant mass distribution, this does not disappear, as shown in Fig. 2.b. In the experimental event reconstruction electrons are often corrected for photon emission effects, but this is not always the case of muons. Thus, one could treat the two cases separately even in the shower simulation, since it is not always true that photon emission from muons leads to negligible effects.

channel	PowHel+SMC 7 TeV (fb)	PowHel+SMC 8 TeV (fb)	ratio
$(e,e)e$	0.516	0.782	1.515
$(e,e)\mu$	0.255	0.388	1.521
$(\mu,\mu)e$	0.273	0.420	1.538
$(\mu,\mu)\mu$	0.613	0.934	1.523
total	1.658	2.524	1.522

channel	PowHel+SMC 7 TeV (fb)	PowHel+SMC 8 TeV (fb)	ratio
$(e,e)$	0.631	0.907	1.437
$(e,\mu)$	0.694	0.991	1.428
$(\mu,\mu)$	1.569	2.289	1.459
total	2.894	4.187	1.446

**Table 1.** Cumulative cross-sections at  $\sqrt{s} = 7$  and 8 TeV, as predicted by PowHel+PYTHIA in a) all trilepton and b) all same-sign dilepton channels. The statistical error is always  $< 1\%$ .

The reconstruction of charged heavy objects like a  $W$  boson or a  $t$ -quark is complicated because the measurement of missing energy, attributed to heavy particle decay, has large uncertainties. As a consequence, we did not introduce any explicit cut to distinguish  $t\bar{t}W$  from  $t\bar{t}Z$  contributions in the analysis in the same-sign dilepton channel. Thus the contribution of the  $t\bar{t}Z$  process is not negligible with respect to that of the  $t\bar{t}W^\pm$  ones, so all three processes contribute in a consistent way to the total amount of observed events, as shown in Fig. 1.b.

The total cumulative cross-sections after full SMC, including the contributions of  $t\bar{t}Z$ ,  $t\bar{t}W^+$  and  $t\bar{t}W^-$ , for all different lepton combinations in the trilepton and dilepton decay channels, at 7 and 8 TeV, are reported in Tables 1.a and 1.b. In the last column of each table, the ratio of the results at 7 and 8 TeV for each single channel is also reported showing an almost constant value. The slightly different average value of this ratio from all trilepton channels, as compared to the average from all dilepton channels, is related to the different set of cuts.

The  $\sqrt{s} = 7$  and 8 TeV PowHel events used for these analyses are freely available on the web at <http://www.grid.kfki.hu/twiki/bin/view/DbTheory/WebHome>.

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## References

- [1] Frixiene S and Webber B R 2002 *JHEP* **0206** 029 (*Preprint hep-ph/0204244*)
- [2] Nason P 2004 *JHEP* **0411** 040 (*Preprint hep-ph/0409146*)
- [3] Frixiene S, Nason P and Oleari C 2007 *JHEP* **11** 070 (*Preprint 0709.2092*)
- [4] Alioli S, Nason P, Oleari C and Re E 2010 *JHEP* **06** 043 (*Preprint 1002.2581*)
- [5] Bevilacqua G, Czakon M, Garzelli M, van Hameren A, Kardos A *et al.* 2013 *Comput.Phys.Commun.* **184** 986–997 (*Preprint 1110.1499*)
- [6] Alwall J, Ballestrero A, Bartalini P, Belov S, Boos E *et al.* 2007 *Comput.Phys.Commun.* **176** 300–304 (*Preprint hep-ph/0609017*)
- [7] Sjostrand T, Mrenna S and Skands P Z 2006 *JHEP* **0605** 026 (*Preprint hep-ph/0603175*)
- [8] Corcella G, Knowles I, Marchesini G, Moretti S, Odagiri K *et al.* 2002 (*Preprint hep-ph/0210213*)
- [9] Garzelli M, Kardos A, Papadopoulos C G and Trócsányi Z 2012 *JHEP* **1211** 056 (*Preprint 1208.2665*)
- [10] Garzelli M, Kardos A, Papadopoulos C G and Trócsányi Z 2012 *Phys.Rev.* **D85** 074022 (*Preprint 1111.1444*)
- [11] Kardos A, Papadopoulos C G and Trócsányi Z 2011 *Phys.Lett.* **B705** 76–81 (*Preprint 1101.2672*)
- [12] Garzelli M, Kardos A, Papadopoulos C G and Trócsányi Z 2011 *Europhys.Lett.* **96** 11001 (*Preprint 1108.0387*)
- [13] Dittmaier S, Dittmaier S, Mariotti C, Passarino G, Tanaka R *et al.* 2012 (*Preprint 1201.3084*)
- [14] Lazopoulos A, McElmurry T, Melnikov K and Petriello F 2008 *Phys.Lett.* **B666** 62–65 (*Preprint 0804.2220*)
- [15] Campbell J M and Ellis R K 2012 *JHEP* **1207** 052 (*Preprint 1204.5678*)
- [16] Kardos A, Trócsányi Z and Papadopoulos C G 2012 *Phys.Rev.* **D85** 054015 (*Preprint 1111.0610*)
- [17] CMS Collaboration 2012 *CMS-PAS-TOP-12-014*.